CLASSIFICATION CANCELLED

Authority NACA Status Sheet Dec '47

By Grace Powell 3-21-51

MAY 14 1947

[redacted]

ARR No. 4A11

[redacted]

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WARTIME REPORT

ORIGINALLY ISSUED

January 1944 as
Advance Restricted Report 4A11

ANALYSIS OF A THERMAL ICE-PREVENTION SYSTEM FOR WING LEADING-EDGE LANDING-LIGHT INSTALLATIONS

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ADVANCE RESTRICTED REPORT

ANALYSIS OF A THERMAL ICE-PREVENTION SYSTEM FOR WING LEADING-EDGE LANDING-LIGHT INSTALLATIONS

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SUMMARY

An analytic study of an extension to the existing B-17F wing leading-edge thermal ice-prevention system is made to include the wing leading-edge landing lights. The procedure and equations are presented in both general and specific form in order that the design will be readily applicable to similar installations.

The analysis indicates that wing leading-edge landing-light installations can be satisfactorily protected against ice formation, and that the system can be incorporated with the wing leading-edge thermal ice-prevention system.

INTRODUCTION

The illumination effectiveness of landing lights installed in the leading edge of airplane wings is often greatly reduced by the formation of ice on the transparency enclosing the light. In addition, the portion of the wing in the region of the light may experience ice formations which would cause undesirable aerodynamic effects. A typical ice formation on a wing leading-edge-type light installation is shown in figure 1.

As a part of an extended program on the design and development of thermal ice-prevention equipment for aircraft, the Ames Aeronautical Laboratory of the National Advisory Committee for Aeronautics has conducted an analytic investigation of the problem of preventing the formation of ice on the transparencies of landing-light installations of the wing leading-edge type.

Although the primary purpose of this analytic investigation was to determine the practicability of providing a landing-light thermal ice-prevention system which could be incorporated with the wing leading-edge thermal ice-prevention system of the B-17F airplane, the analysis has been developed in a general form for future application to similar designs.

The investigation has been conducted at the request of the Materiel Command, U. S. Army Air Forces.

DESCRIPTION OF PROPOSED SYSTEM

In the typical wing leading-edge landing-light installation, the light itself is mounted in a web running spanwise and at approximately right angles to the wing chord. The wing skin forward of the light is formed from a transparent plastic through which the light beam passes. It is because of the formation of ice on this plastic that the light beam loses its effectiveness. By sufficiently heating the plastic leading edge, the landing-light installation may be protected from the formation of ice. To effect this protection it is proposed to pass heated air from the wing leading-edge thermal ice-prevention system spanwise through the space between the plastic leading edge and the face of the light lens. In general, the necessary revisions to the typical installation to provide ice protection consists of reducing the area of the transparent plastic leading edge to a minimum and providing the metal skin surrounding the plastic with an inner skin similar to that used in the wing leading-edge ice-prevention system.

The existing landing-light installation in the B-17F airplane (fig. 2) consists of a sealed-beam lamp supported in a web which is located parallel to the wing leading edge at approximately 6 percent of the chord behind the leading edge. The leading edge of the wing between wing stations 18 and 19, approximately 16 inches, consists of a formed transparent plastic sheet 1/8 inch thick extending from the 1½-percent-chord point on the upper surface around the leading edge to approximately the 6-percent-chord point on the lower surface. The plastic leading edge is readily removable, thereby facilitating replacement of the lamp.

The recommended alterations to the landing-light installation on the B-17F airplane to provide ice protection are shown in figure 3. The front face of the lamp is shown moved forward to approximately the 3-percent-chord point, the web supporting the lamp is made parallel with the surface of the lens insofar as possible, and the space between the lens and the leading edge is sealed to form a plenum chamber connected to the wing leading-edge ice-prevention system. The area of the plastic leading edge has been reduced to the minimum area consistent with the requirements of Army specification 94-32265-B which governs the angle of divergence necessary for the passage of the light beam, and consistent with the clearance necessary to remove the light lens and supporting frame. The metal surface of the wing surrounding the transparency has been provided with an inner skin similar to that used in the wing leading-edge ice-prevention system; and the forward portions of the ribs at stations 19 and 19A have been removed from the region between the leading edge and the web to provide for unrestricted flow spanwise from the 5-inch-diameter heated-air supply duct through the landing-light plenum chamber into the normal wing leading-edge ice-prevention system. The supply duct will discharge into the leading-edge system at wing station 18 instead of between wing stations 20 and 21, as is the case in the existing ice-prevention system.

SYMBOLS

A_c cross-sectional area, sq ft

A_s surface area, sq ft

b thickness of transparency, in.

c wing chord, in.

D_e equivalent diameter, 4m, ft

G mass velocity, $W/3600A_c$, lb/sec, sq ft

h surface heat-transfer coefficient, Btu/hr, sq ft, deg F

k thermal conductivity of transparency, Btu/hr, sq ft, deg F/in.

k' thermal conductivity of air, Btu/hr, sq ft, deg F/ft

m hydraulic radius, A_c/P_w, ft

P_w wetted perimeter, ft

Q heat-transfer rate, Btu/hr

Re Reynolds number, $\frac{4mG}{\mu}$, dimensionless

t temperature, deg F

U over-all heat-transfer coefficient, Btu/hr, sq ft, deg F

v specific volume, cu ft/lb

W flow rate, lb/hr

x distance chordwise from wing leading edge, in.

μ absolute viscosity, lb/sec, ft

Subscripts

1 plenum chamber

2 inner surface of wing skin

3 outer surface of wing skin

4 atmosphere

av average value

ANALYSIS

The analysis is concerned only with the prevention of ice on the transparency in the leading edge of the wing directly forward of the landing light. The analysis of the double-skin structure surrounding the transparency is similar to that previously developed for the thermal ice-prevention equipment of wing leading edges (reference 1).

In applying the analysis to a specific example, it is necessary to choose a set of flight conditions under which the system is to operate. These assumed conditions for the B-17F airplane as taken from reference 1 are as follows:

1. Indicated airspeed, 155 miles per hour at 18,000 feet pressure altitude

2. Ambient-air temperature, 0° F

3. Temperature of air from exchangers, 320° F

4. Flow rate of air from exchangers, 2730 pounds per hour (all air to be supplied to outer wing panel through plenum chamber)

The heat transfer for the landing-light installation is divided into three parts for the purpose of analysis: (1) heat transfer from the outer surface of the transparency to the atmosphere, (2) heat transfer through the transparency, and (3) heat transfer from the hot air to the inner surface of the transparency.

Heat transfer from the outer surface of the transparency to the atmosphere.- At the outset it is necessary to choose a temperature rise of the outer surface of the skin above ambient atmosphere, $t_3 - t_4$, which will prevent the formation of ice on the transparency. Previously (reference 1), it has been assumed that an average rise of 90° F is required over the leading edge of the wing (back to the 15-percent-chord point on both surfaces), and tests under natural icing conditions have verified the fact that this rise is satisfactory.

In preliminary calculations it was found that in order to achieve this temperature rise on the surface of the transparency the maximum temperature reached by the inner surface of the plastic was above 200° F which is a value chosen to provide a margin of safety below the softening temperature of the plastic. Two solutions were available by which the maximum temperature of the inner surface could be reduced. The first was to reduce the temperature gradient through the transparency by reducing its thickness, or by choosing a material having a higher conductivity. The second was to reduce the heat transfer to the inner surface, which would also result in a lower average temperature on the outer surface.

In the application to the B-17F airplane the second solution was chosen since the thickness of the plastic could not be reduced for structural reasons, and a plastic having a higher conductivity was not available. A subsequent calculation indicated that in order to keep the maximum temperature of the inner surface below 200° F the average temperature of the outer surface should not exceed 75° F. This value is chosen as the basis of the analysis recognizing the fact that the prevention of ice in this case will be marginal.

Since the analysis of future installations probably will be based on the assumption of the average temperature required on the outer surface of the plastic, the equations in this report are developed with the assumption of the average outer-surface temperature as a starting point.

At a point on the transparency the unit heat transfer from the surface to the atmosphere is defined by

$$\frac{Q_{3-4}}{A_s} = h_{3-4}(t_3 - t_4) \tag{1}$$

where the subscripts refer to regions indicated in figure 3.

The values of h_{3-4} over the laminar region of the wing are obtained by applying the method presented in reference 2 to the specific case. These values for the B-17F wing are plotted in figure 4.

The plastic leading-edge surface for the proposed B-17F installation extends between $1\frac{1}{2}$ percent of the wing chord on the upper surface and 3 percent of chord on the lower surface (fig. 3). An average value of h_{3-4} for this region equal to 16 Btu per hour, square foot, °F is obtained from figure 4.

The average unit heat-transfer rate corresponding to these conditions is found by substituting into equation (1)

$$\left(\frac{Q_{3-4}}{A_s}\right)_{av} = 16 \times 75$$

$$= 1200 \text{ Btu per hour, square foot}$$

<u>Heat transfer through transparent region</u>.- The transparent materials currently employed in aircraft manufacture possess a very low coefficient of heat conductivity. For glass, the conductivity, k, is 3 to 7 Btu per hour, square foot, °F per inch. According to information obtained from manufacturers of the respective plastics, the values of thermal conductivity are 1.5 to 2.1 for methyl methacrylate resin (Lucite), and 1.45 for Columbia resin (CR-39).

Although glass has the higher thermal conductivity, plastic is chosen because its advantages of easy forming and replacement are believed to outweigh its relatively poor thermal conductivity. The thinnest gage that will fulfill structural requirements should be used so as to minimize both the resistance to heat flow and temperature of the inner surface.

Heat transfer through the transparency is defined by the fundamental equation for conduction

$$Q_{2-3} = \frac{k}{b} A_s \,(t_2 - t_3) \tag{2}$$

By rearranging terms, the temperature gradient through the transparency is

$$t_2 - t_3 = \frac{Q_{2-3}\, b}{k\, A_s} \tag{2a}$$

Using an average value of $k = 1.75$ for the plastic transparency and a thickness, b, of 0.125 inch, which is the same as that of the present B-17F installation, the average temperature gradient through the plastic required for an average unit heat-transfer rate of 1200 Btu per hour, square foot, as obtained from equation (2a), is

$$t_{2_{av}} - t_{3_{av}} = \frac{Q_{2-3}}{A_s}\,\frac{b}{k}$$

$$= \frac{1200 \times 0.125}{1.75}$$

$$= 86^\circ\ F$$

Since the average value of t_3 is 75° F, the average value of t_2 becomes 161° F.

Heat transfer from hot air to transparency.- For a fixed heated-air-flow rate and temperature, the surface heat-transfer coefficient from the air to the inner surface of the transparency, h_{1-2} will vary according to the cross-sectional area of the plenum chamber (fig. 3). This relationship is expressed by the following equation for heat transfer from a fluid flowing in a pipe as taken from reference 3 and expressed in the symbols of this report:

$$\frac{h_{1-2} D_e}{k'} = 0.02 \ (Re)^{0.8} \tag{3}$$

Applying the conditions assumed for the B-17F airplane

$$h_{1-2} = \frac{0.0004}{D_e} \ (Re)^{0.8}$$

The variation of surface heat-transfer coefficient with cross-sectional area of the plenum chamber as derived from the above equation is shown in figure 5. For the B-17F airplane the approximate location of the web in which the light is mounted corresponding to the cross-sectional areas is also shown.

Solving for the surface heat-transfer coefficient in the general equation,

$$h_{1-2} = \frac{Q_{1-2}}{A_s \ (t_1 - t_2)} \tag{4}$$

by substituting the proper numerical values

$$h_{1-2} = \frac{1200}{320-161} = 7.5 \text{ Btu per hour, square foot, } ^\circ\text{F (approx.)}$$

For a value of h_{1-2} equal to 7.5, the cross-sectional area of the plenum required to effect the heat-transfer rate is found in figure 5 to be 0.27 square foot, and the rearmost light location is established at approximately 3 percent of the chord.

It is noted that the degree of turbulence in the heated air stream and the direction of air flow across the landing-light installation will affect the heat-transfer coefficient, h_{1-2}. If the approach duct directs the air to the transparent plastic, a higher-heat-transfer coefficient may be expected.

Throughout this analysis the surface of the light lens has been assumed to be parallel to the leading edge of the wing. An inspection of figure 3 will reveal that this assumption is not strictly correct, and that the cross-sectional area of the plenum between the wing skin and light surface varies in a spanwise direction. In the application of this analysis to the B-17F airplane, however, the spanwise variation in cross-sectional area has been considered small enough to be disregarded, and the web should be located so that the required area (0.27 sq ft) is near the center of the light.

If it is found that the value for the required plenum area falls on the region of the curve in figure 5 where the heat-transfer coefficient is varying rapidly with a change in cross-sectional area of the plenum, and if in the actual installation the cross-sectional area varies an appreciable amount across the face of the lamp, it may be desirable to analyze the system at both edges of the lamp. In such a case provision may be required to prevent overheating one edge of the plastic and underheating the other.

<u>Heat transfer and temperature gradient around leading edge of the wing</u>.- Because of the rapid variation of outer-surface heat-transfer coefficient with percent of wing chord, as shown in figure 4, it is desirable to determine the chord-wise distribution of the heat transfer and surface temperatures in the region of the transparency. These are determined by the calculation of the over-all coefficient of heat transfer U_{1-4}. (See reference 3.)

$$\frac{1}{U_{1-4}} = \frac{1}{h_{1-2}} + \frac{b}{k} + \frac{1}{h_{3-4}}$$

$$U_{1-4} = \frac{h_{1-2}\ k\ h_{3-4}}{h_{3-4}\ k+b\ h_{1-2}\ h_{3-4} + h_{1-2}\ k} \qquad (5)$$

Substituting the values which are independent of chord

$$U_{1-4} = \frac{7.5 \times 1.75 \times h_{3-4}}{1.75\ h_{3-4} + 0.125 \times 7.5\ h_{3-4} + 7.5 \times 1.75}$$

$$= \frac{13.1\ h_{3-4}}{2.69\ h_{3-4} + 13.1}$$

The unit heat-transfer rate at any point on the transparency is represented by

$$\frac{Q}{A_s} = U_{1-4}\ (t_1 - t_4) \tag{6}$$

Substituting the values of temperature and the values of U_{1-4} determined from equation (5) and figure 4, the unit heat-transfer rates shown in figure 6 are calculated for the B-17F airplane. Employing these values of Q/A_s and those of h_{3-4} from figure 4 the temperature distributions over the inner and outer surfaces of the plastic (t_2 and t_3) were calculated from equations (1) and (2a) and are presented in figure 6.

DISCUSSION

Based on experience gained in flights under natural icing conditions, it is thought that the protection provided against the prevention of ice with the outer surface of the plastic at 75° F above ambient air will be marginal. It is possible that ice will form at the stagnation point because of the low local temperature, but chordwise growth will be impeded by the rapidly increasing surface temperature (fig. 6). In the stagnation region the formation of ice will be intermittent since it acts as an insulation to the escape of heat. The resulting rise in surface temperature loosens the bond at the surface and the formation is blown off.

As is evidenced by inspection of figure 6, the entire inner surface of the plastic for the B-17F installation is below the temperature of 200° F which was set as an upper limit and, therefore, heat-resisting plastics may be used in fabricating the transparent leading edge. Several such plastics are available which retain the required strength and resistance to deformation at temperatures ranging from 200° to 250° F.

Flight tests of an installation in icing conditions are recommended where it is anticipated that the formation of ice will be marginal, as in this case where the average surface temperature rise is less than the recommended rise of 90° F above ambient air. Such tests are considered unnecessary where the 90° F temperature condition is met.

The total surface area of transparency required is less than 1 square foot, and at an average unit heat-transfer rate of 1200 Btu per hour, square foot, the heat required is less than 6/10 of 1 percent of the total heat available for the thermal ice-prevention system at the B-17F outer wing panel.

In reference 1 it was found that the spanwise pressure drop for the B-17F airplane is very low, and so it was not calculated in this analysis since the cross-sectional area of the plenum at the light is comparable to that of the heated-air supply duct for the wing outer panel. Any protuberances in the duct, however, will cause an increase in pressure drop and therefore should be avoided. Likewise the transition between the plenum in the light and the outer-panel plenum should be as gradual as possible.

CONCLUDING REMARKS

The analysis herein indicates that an average temperature rise of 75° F above ambient air can be obtained on the outer surface of the B-17F wing leading-edge landing-light installation, without exceeding the maximum allowable inner-surface temperature of 200° F. Experience gained in flights under natural icing conditions at ambient-air temperatures around 0° F indicates that the ice protection afforded by this installation would be marginal, but that any formations experienced probably would be confined to the stagnation region and would be intermittently removed. In view of certain assumptions made in the analysis, experimental verification in the form of construction and tests of a typical installation is recommended.

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Figure 1.- Formation of ice on the unprotected landing-light installation on the B-17F airplane.

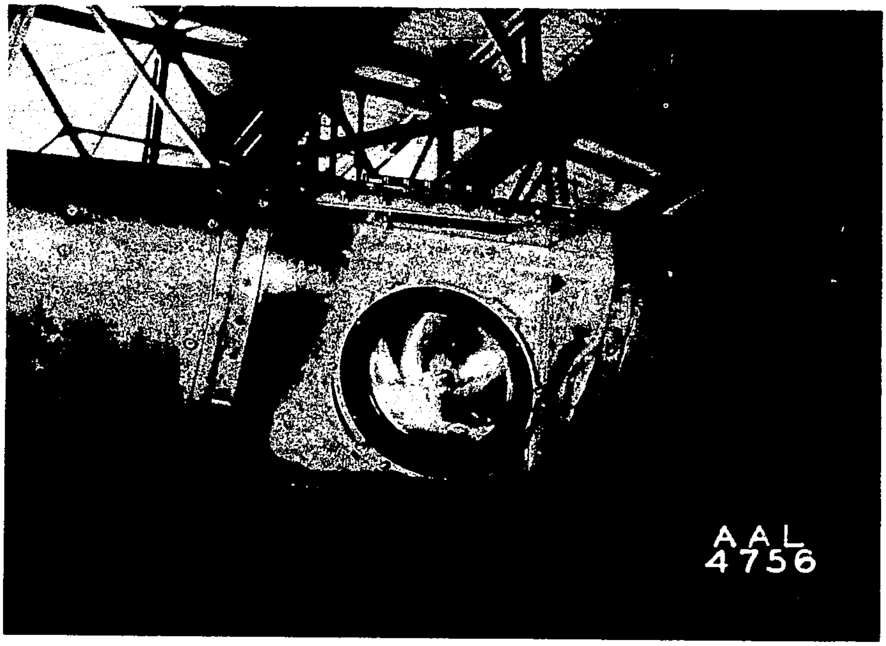

Figure 2.-Existing wing leading-edge landing-light installation on the B-17F airplane.

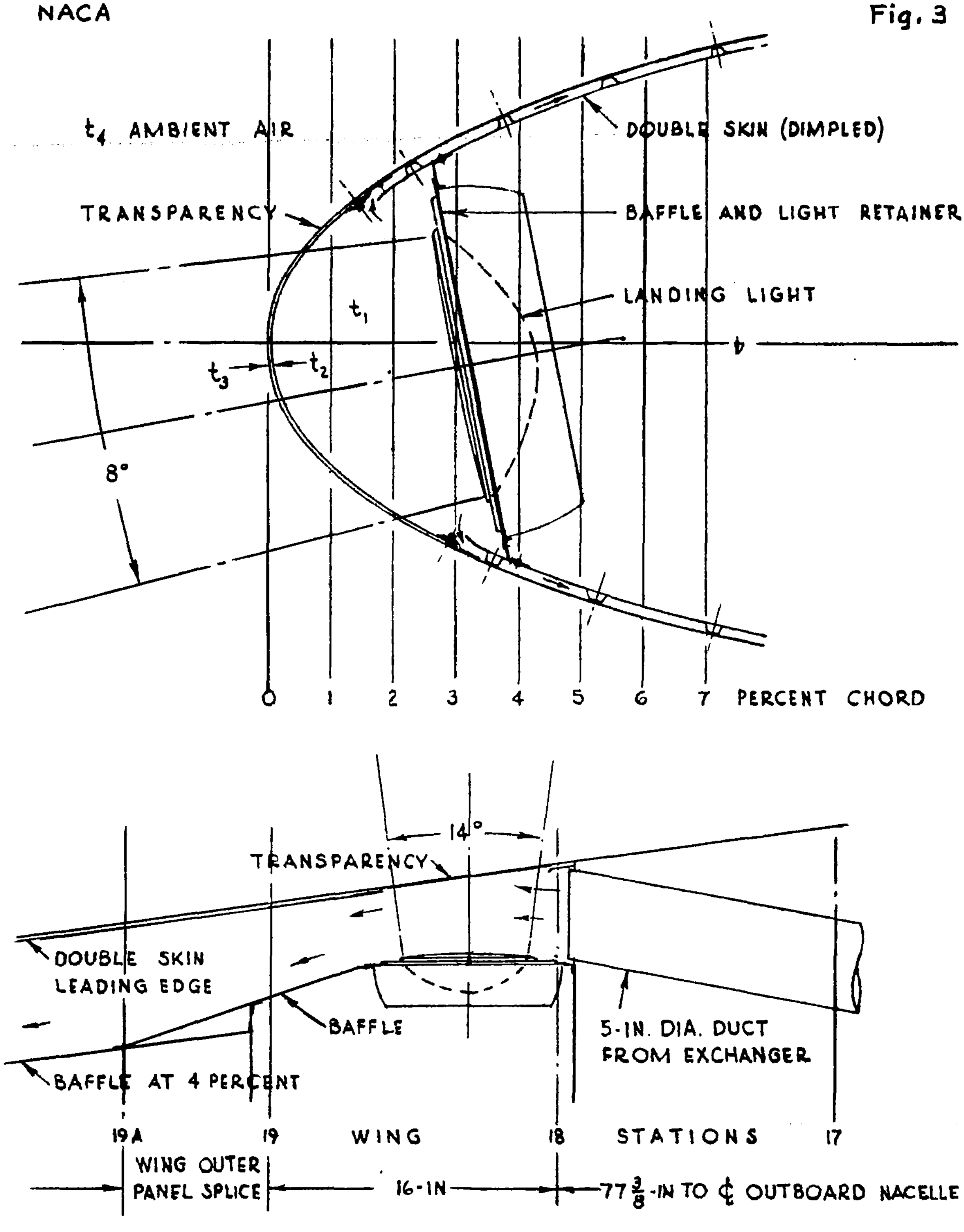

FIGURE 3 - PROPOSED LANDING LIGHT INSTALLATION ON THE B-17F AIRPLANE EQUIPPED FOR THERMAL ICE PREVENTION.

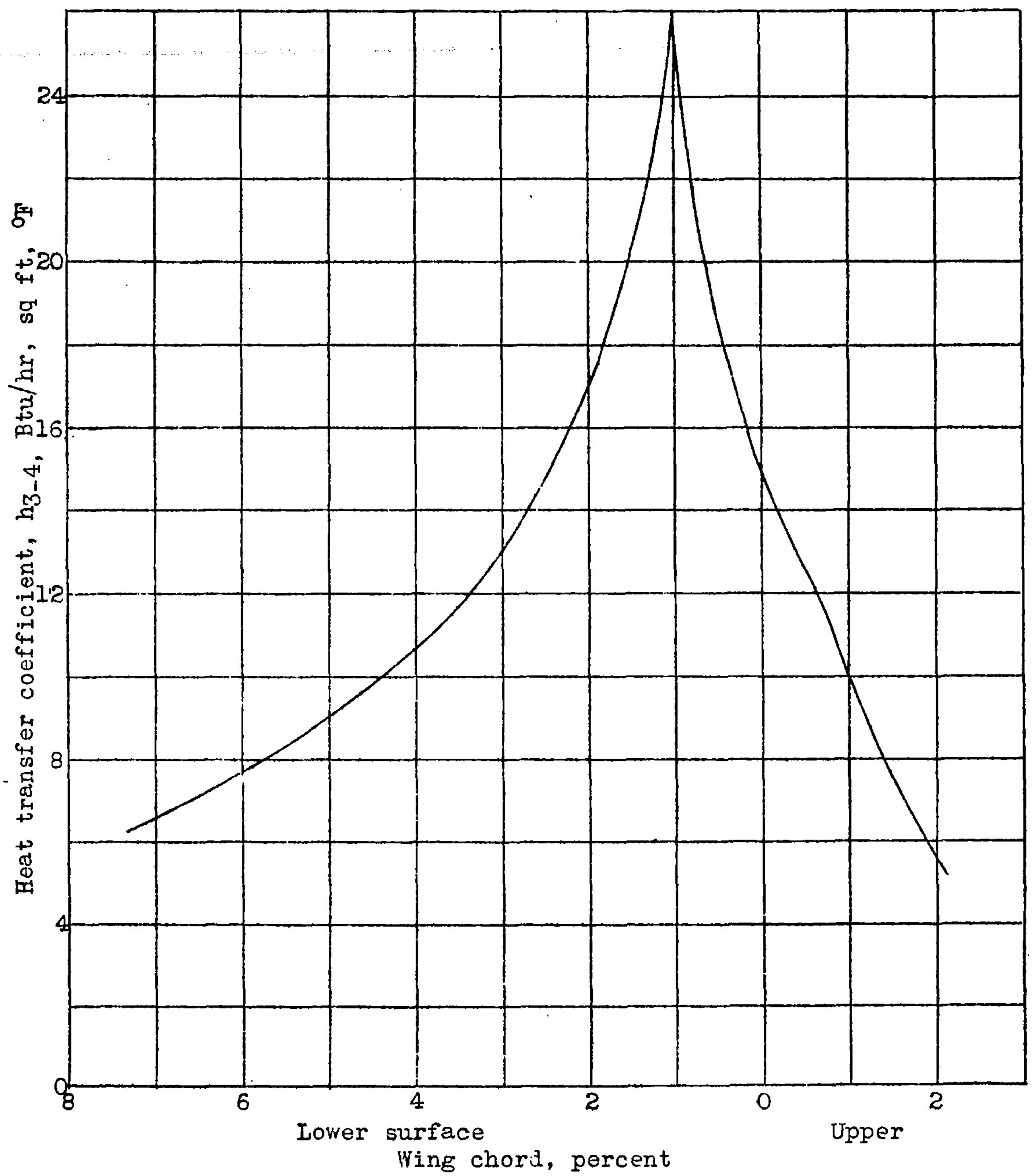

Figure 4.- Surface heat transfer coefficients in laminar region of B-17F wing leading edge at station 19 determined by method of reference 2.

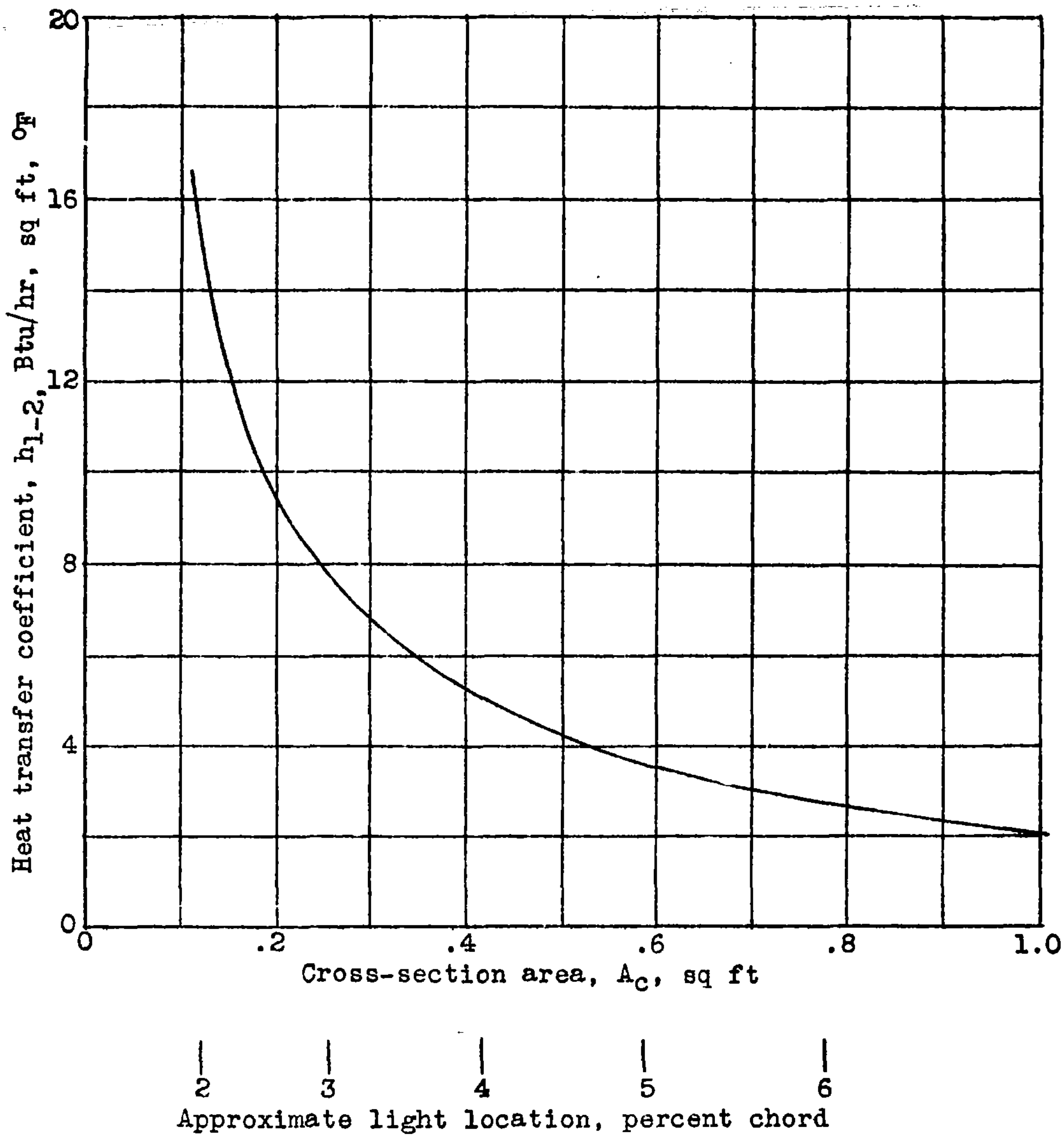

Figure 5.- Variation of inner-surface heat transfer coefficient with cross-sectional area of plenum.

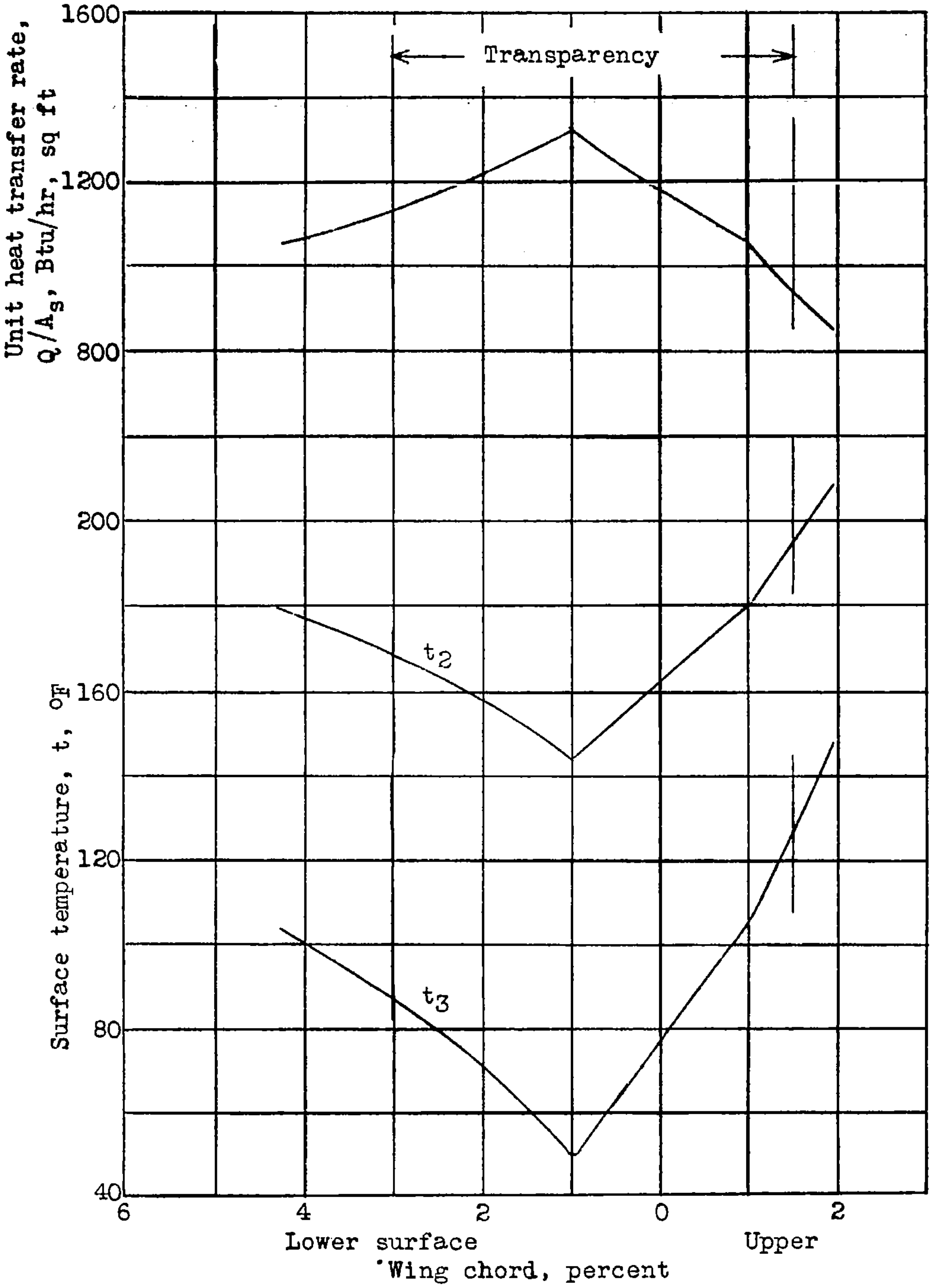

Figure 6.- Variation of unit heat transfer rate and surface temperatures with percent of wing chord at station 19 for 0.125 plastic skin, and web at approximately 3 percent of chord.